The N2K Consortium. VII. Atmospheric Parameters of 1907 Metal-Rich Stars: Finding Planet-Search Targets

Sarah E. Robinson[1], S. Mark Ammons[1], Katherine A. Kretke[1], Jay Strader[1], Jeremy G. Wertheimer[1], Debra A. Fischer[2], and Gregory Laughlin[1]

ABSTRACT

We report high-precision atmospheric parameters for 1907 stars in the N2K low-resolution spectroscopic survey, designed to identify metal-rich FGK dwarfs likely to harbor detectable planets. 284 of these stars are in the ideal temperature range for planet searches, $T_{\rm eff} \leq 6000$K, and have a 10% or greater probability of hosting planets based on their metallicities. The stars in the low-resolution spectroscopic survey should eventually yield > 60 new planets, including 8-9 hot Jupiters. Short-period planets have already been discovered orbiting the survey targets HIP 14810 and HD 149143.

Subject headings: planetary systems—stars: abundances, methods: statistical

1. Introduction

The peak year for planet discovery by radial velocity searches was 2002, with 34 new planets discovered. Since then, the planet discovery rate has flattened out, with 27 new planets discovered in 2004 and another 27 in 2005[1]. The volume within 25 pc of the Sun—$V < 7$ for a Solar-type star—has been thoroughly searched for short-period giant planets, or hot Jupiters. Future planet searches focusing on this volume of space will be aimed at either low-mass planets, as in the forthcoming Automated Planet Finder survey at Lick Observatory, or long-period planets, as in the Nakajima et al. (2005) coronagraphic-adaptive optics search for brown dwarfs and planets around nearby ($d < 20$ pc) young stars. Searches

[1]University of California Observatories/Lick Observatory, Department of Astronomy and Astrophysics, University of California at Santa Cruz, Interdisciplinary Sciences Building, Santa Cruz, CA 95064, ser@ucolick.org, ammons@ucolick.org, kretke@astro.ucsc.edu, jwerthei@ucolick.org, laughlin@ucolick.org

[2]Department of Physics & Astronomy, San Francisco State University, San Francisco, CA 94132, fischer@stars.sfsu.edu

[1]Source: Interactive Extra-solar Planets Catalog, http://vo.obspm.fr/exoplanetes/encyclo/catalog.php

for new short-period planets must push out to larger distances and fainter stars in order to add to the 48 planets with periods $P < 7$ d (the upper limit for a tidally circularized orbit) known at the time of this writing.

A primary reason the N2K Consortium focuses on discovering hot Jupiters is their high probability of performing detectable transits. Since the radii of transiting planets can be measured directly, they provide valuable information about planetary composition. Indeed, planetary interior models indicate that HD 149026 b, while having an observed mass comparable to that of Saturn, has the largest solid core, $70M_{\oplus}$, of any known planet (Sato et al. 2005; see also Fortney et al. 2005). In comparison, Jupiter has a core mass of $0 - 11M_{\oplus}$ and Saturn has a core mass of $9 - 22M_{\oplus}$ (Saumon & Guillot 2004). It is also important to quickly locate short-period planets orbiting bright parent stars because these objects can be profitably observed with the *Spitzer Space Telescope* during its limited cryogenic lifetime. Williams et al. (2006) show that *Spitzer* Infrared Array Camera secondary eclipse light curves can probe the variation of hot Jupiter thermal emission across the surface of the planet—for example, day-night temperature difference and presence of hot or cold spots.

The N2K project (Fischer et al. 2005) was created to facilitate the detection of new exoplanets, especially hot Jupiters, by identifying the "Next Two Thousand" metal-rich stars suitable for precise radial-velocity measurements. The observational efficiency of the first-generation California-Carnegie planet search (Marcy et al. 2005) of $V < 7$ stars was limited by readout and telescope slew time—total ~ 1 minute per target with the HIRES spectrograph. However, for stars with $V > 7$, exposure time becomes the limiting factor on observing efficiency. To keep the planet detection rate per hour of scientifically valuable short-period planets on par with its 2002 peak, we must make sure each target star has a high probability of harboring a detectable planet. The first generation of planet searches uncovered the planet-metallicity correlation (Gonzalez 1997): doubling the metal content of a Solar-type star leads to a fourfold increase in its probability of harboring a detectable planet (Fischer & Valenti 2005). By measuring the metallicity of thousands of FGK dwarfs in the Solar neighborhood with published photometry and small-telescope observations, we can identify the most productive targets for the ongoing Keck/Subaru/Magellan (hereafter KSM) planet search.

The N2K consortium sieves targets for the KSM planet search using successive metallicity estimates of increasing precision. The first step in the N2K pipeline is identifying FGK dwarfs in the Hipparcos catalog (Perryman et al. 1997) that have not already been searched for planets and have either 2MASS JHK photometry (Skrutskie et al. 2006) or $ubvy\beta$ photometry (Nördstrom et al. 2004). As most Hipparcos stars have $V < 10$ and stars with $V < 7$ have, with few exceptions, already been searched for planets, most of our candidate stars have apparent magnitudes $7 < V < 10$. For stars with Hipparcos BV and 2MASS JHK photometry, we use the empirical relation between broadband colors and metallicity calculated by Ammons et al. (2006) to estimate [Fe/H]. This calibration has precision $\sigma = 0.17$ dex for stars with $V < 9$. For the stars with $ubvy\beta$ photometry, we use the [Fe/H] estimates reported in the Nordström et al. (2004) compilation, most of which were calculated using the Schuster & Nissen (1989) $ubvy$-metallicity calibration, with precision $\sigma = 0.13$ dex.

Stars with metallicity estimates of [Fe/H] = 0.0 dex or higher from either broadband or $ubvy\beta$ photometry proceed to the second level of N2K screening. At this level, we obtain a low-resolution optical spectrum of each star and measure the Lick indices, which are broad atomic and molecular features between 4000 and 6000 Å. We then use the empirical calibrations reported by Robinson et al. (2006, hereafter Paper 1) that give [Fe/H], $T_{\rm eff}$ and $\log g$ as functions of selected Lick indices (Worthey et al. 1994). The relatively high precision of these calibrations—$\sigma_{\rm [Fe/H]} = 0.07$ dex, $\sigma_{T_{\rm eff}} = 82$K, and $\sigma_{\log g} = 0.13$ dex—enables us to create clean target lists composed of metal-rich, cool stars with high probabilities of planet detection for the ongoing Keck/Subaru/Magellan planet search. Note that, as our low-resolution spectra were obtained at Kitt Peak National Observatory, there is a large, unsurveyed population of Hipparcos/2MASS stars with declinations below -20^o. The Keck planet search also includes bright stars for which the photometric metallicity estimates were precise enough to skip low-resolution screening.

The first planet discovered by the N2K Consortium was HD 88133 b (Fischer et al. 2005), a Saturn-mass planet with $P = 3.41$ d. The next discovery was the transiting hot Saturn orbiting HD 149026 (Sato et al. 2005). The N2K consortium then reported two more short-period planets, HD 149143 b and HD 109749 b (Fischer et al. 2006). HD 149143 b is a hot Jupiter, with minimum mass $M \sin i = 1.33 M_J$ and $P = 4.072$ d. Finally, Wright et al. (2007) discovered two planets orbiting the N2K target HIP 14810, the hot-Jupiter b component ($P = 6.67$ d) and the long-period c component. In this paper, we report the results of our low-resolution spectroscopic survey of 1907 stars. Two of N2K's newly discovered planet hosts, HD 149143 and HIP 14810, were part of the low-resolution spectroscopic survey.

2. Observations and Lick Index Measurements

Our observations were taken at the 2.1m telescope at Kitt Peak National Observatory during three observing runs, UT dates 2004 August 27-September 2, 2005 March 26-April 1, and 2005 April 23-29. A fourth observing run, 2005 February 10-16, was rained out. We used the GoldCam spectrograph with a 600 lines mm^{-1} grism blazed at 4900 Å. The spectral coverage was 3800-6200 Å with $R = 1360$ (FWHM = 3.7 Å) at 5000 Å. A typical spectrum has S/N $\sim$ 230 per resolution element (120 per Å) in the Ca4227 line, the shortest-wavelength index measured, increasing to S/N $\sim$ 380 per resolution element (200 per Å) in the Na D index. As Lick indices are independent of absolute flux levels (Worthey & Ottaviani 1997), our spectra were not flux calibrated.

Since our observing program was designed to survey as many potential planet-search targets as possible, we did not take a comparison-lamp spectrum at each telescope position. Rather, we obtained wavelength solutions accurate to $\sigma \sim 4$ Å by observing comparison lamps only at the beginning, middle and end of each night. Following the method of Paper 1, we used an unsharp masking algorithm to find the center of each spectral line used in the Lick indices-atmospheric parameter calibrations. We smoothed each spectrum using a Gaussian low-pass filter and subtracted the smoothed spectrum from the original spectrum. We then searched the unsharp-masked spectrum for local minima with 12 Å of each known line center. Comparing line centers found by the automatic recentering program with those measured by hand using Gaussian-fit tools in IRAF for three spectra led us to estimate an error of ± 2 Å in our recentered wavelength solutions. According to Worthey et al. (1994), the contribution of wavelength errors of this magnitude to errors in Lick indices is negligible.

The calibrations reported in Paper 1 use the bandpass definitions of Trager et al. (1998) for the indices Ca4227, G4300, Fe4383, Fe4531, Fe4668, Hβ, Fe5015, Mg$_2$, Mg b, Fe5270 and Na D; and the bandpass definition of Worthey & Ottaviani (1997) for Hγ_F. We measured Lick indices in our spectra using the publicly available `indexf` code,[2] which incorporates the error analysis techniques of Cardiel et al. (1998). Since the Paper 1 calibrations are based in part on observations with slightly lower resolution than the original IDS spectra, we did not smooth our spectra to match the IDS resolution. Measuring Lick indices using spectra with lower resolution than the original IDS spectra slightly increases the random error in each index, (Worthey & Ottaviani 1997), but does not add any systematic errors.

We transformed our data to the Lick system using observations of Lick standard stars, which have indices reported in Worthey et al. (1994) and Worthey & Ottaviani (1997). 79 observations of 62 standard stars were obtained during the observing run in August 2004; 24 observations of 23 stars were obtained during the March 2005 run; and 38 observations of 27 stars were obtained during the April 2005 run. The observed Lick standards were mainly FGK dwarfs, matching the spectral types of our program stars, but a few B and A-type dwarfs were also observed in parts of the sky where FGK Lick standards were not

[2]Created by Cardiel, Gorgas, & Cenarro, released on 2002 July 11

available. For each index, we used least-squares analysis to find a linear fit between the published equivalent width and the equivalent width measured from our data. In order for the fits to metal lines not to be biased by extremely metal-poor stars, data points that were more than 3 standard deviations away from the line of best fit were rejected and the fits were computed again. Rejecting deviant points also kept cool stars with no discernible Balmer absorption from biasing the fits to the indices measuring Balmer lines, Hγ_F and Hβ. Since the alignment of the GoldCam spectrograph changes slightly each time it is taken down and re-mounted on the telescope, we computed separate transformations to the Lick system for each observing run. The index measurement errors and transformations from observed to published Lick indices are given in Table 1, and the Lick indices for our survey targets are given in Table 2. Figure 1 compares our measured Lick indices with published values for all the Lick standard stars in our sample.

Rapidly changing temperatures on 2005 April 27 led to an unstable telescope focus, and suboptimal spatial profiles of spectra obtained that night. Although spectra with wide spatial profiles as a consequence of changing focus have reduced signal-to-noise ratio in each line, the data obtained this night are still above the minimum S/N = 100 per Å. We see no systematic offsets in Lick index measurements for the standard stars observed that night, and conclude that the accuracy of data from 2005 April 27 is unimpaired.

3. Measuring Atmospheric Parameters

During our KPNO observing program, we surveyed and measured the atmospheric parameters of 1907 FGK dwarfs identified as metal-rich by either Ammons et al. (2006) or Nordström et al. (2004). [Fe/H], $T_{\rm eff}$ and log g were measured using the calibrations presented in Paper 1, which were built by obtaining low-resolution spectra of stars in the Valenti & Fischer (2005, hereafter VF05) planet-search catalog and finding empirical relations between selected Lick indices and the atmospheric parameters reported in VF05. In the Paper 1 fits, $T_{\rm eff}$ is given by a linear combination of Lick indices; [Fe/H] is a linear combination of Lick indices and $T_{\rm eff}$; and log g is given by linear terms in each of the Lick indices and $T_{\rm eff}$ plus one nonlinear term, $T_{\rm eff}({\rm H}\gamma_F + {\rm H}\beta)$. To verify the precision and accuracy of the fits in Paper 1, we obtained 191 observations of 127 stars in the VF05 catalog during the 3 KPNO observing runs. By comparing the atmospheric parameters measured from KPNO spectra with the VF05 values, we could compare the true performance of the [Fe/H], $T_{\rm eff}$ and log g calibrations with the published uncertainties. Figure 2 gives scatter plots showing the performance of each calibration. Stars that were included in the training set used to build the Paper 1 calibrations are shown in black, and stars that were used only for testing the calibrations ("test set") are shown in gray. A visual inspection of Figure 2 reveals that the calibrations accurately reproduce the VF05 atmospheric parameters.

In Paper 1, the calibration errors are modeled by fitting a Gaussian to the residuals ($[Fe/H]_{KPNO}$) – ($[Fe/H]_{VF05}$). According to the Gaussian error model, 68% or more of the stars in any test set should have atmospheric parameter estimates within 1σ of the VF05 values if the calibrations are performing within the published error estimates. The test set in this work consists of 79 observations of 48 stars, and the Paper 1 calibration uncertainties are $\sigma_{T_{\rm eff}} = 82$K, $\sigma_{\rm [Fe/H]} = 0.07$ dex, and $\sigma_{\log\, g} = 0.13$ dex. 66% of the $\log g$ measurements are within 1σ of the VF05 values; 72% of [Fe/H] measurements are less than 1σ from the VF05 values; and fully 91% of $T_{\rm eff}$ measurements are within 1σ of VF05 values, indicating a possible slight overestimation in our reported error on $\sigma_{T_{\rm eff}}$.

At the time of this writing, 233 of the stars observed at KPNO had subsequently been observed with the Keck HIRES spectrograph, and [Fe/H] measured. In Figure 3, KPNO [Fe/H] values are compared with the Keck [Fe/H] measurements. The standard deviation of ($[Fe/H]_{KPNO}$) - ($[Fe/H]_{Keck}$) is 0.07 dex, as given in Paper 1, and the center of this distribution is -0.03 dex. As this 0.03-dex offset in the [Fe/H] zero point is robust in the range $0.00 \leq$ $[Fe/H \leq 0.25$, a critical range for planet searches, we suggest measurements in future surveys using the Paper 1 method be corrected by this value. We also note that the training set for the [Fe/H] calibration consisted of FGK dwarfs with approximately solar composition: we do not expect the calibration to retain its precision or accuracy if used on stars with a different abundance mixture.

Our test of the Paper 1 calibrations demonstrates their precision and ease of use. A single low-resolution spectrum, obtained with a 40-second exposure for a $V = 8$ star at the 2.1m telescope, leads to [Fe/H] measurements that rival the precision of the high-resolution spectroscopy in the Cayrel de Strobel, Soubiran & Ralite (2001) compilation. (Of course, since a high-resolution spectrum can be used to measure the abundances of many elements, the Paper 1 calibrations certainly do not obviate the need for high-resolution spectroscopy in characterizing stellar populations.) We measure Lick indices using a publicly available code and use simple linear transformations, based on observations of stars in the catalogs of Worthey et al. (1994) and Worthey & Ottaviani (1997), to place our measurements on the published Lick system. Of order 30 observations of Lick standards per observing run are enough to define transformations onto the Lick system, and a further ~ 30 observations of VF05 stars per observing run verify the accuracy of the Paper 1 calibrations for each new data set. During the observing run of 2004 August 27-September 2 (the only one of our observing runs where we did not lose time due to poor weather), we were able to screen 984 potential planet-search targets, in addition to observing 90 VF05 stars to improve the calibrations. Although some pre-screening based on broadband photometry is necessary to make sure targets are Population I FGK dwarfs, our calibrations make high-throughput observing programs that return precise measurements of stellar atmospheric parameters possible.

4. Results: Planet-Search Targets

The goal of our KPNO observing program was to identify stars that are cool enough for successful radial-velocity measurements, and metal-rich enough to have high probabilities of planet detection. The ideal upper temperature limit of planet-search targets is 6000K, because hotter stars tend to be rapidly rotating. Rapid rotators have broad spectral lines that interfere with measuring precise radial velocities. Planet searches have been successful for stars in the range 6000-6400K, spectral type F5-F9, although these stars can exhibit δ Scuti-type quasi-periodic velocity variations that exceed estimates of stellar jitter (Galland et al. 2006). For late F stars, care must be taken to ensure that periodic radial velocity variations are maintained for several periods, so that that stellar pulsations do not masquerade as short-period planets. Well-known examples of planet hosts within the temperature range 6000-6400K are υ And b (HD 9826 b; Butler et al. 1997), HD 209458 (Henry et al. 2000, Charbonneau et al. 2000) and τ Boo (HD 120136; Butler et al. 1997).

Stars hotter than 6400K have weak metal lines unsuitable for high-precision radial-velocity fits. In Paper 1, we give the ranges in $T_{\rm eff}$, [Fe/H] and log g covered by the training sets from which the calibrations were built: 4100K $< T_{\rm eff} <$ 6400K, -0.95 dex $<$ [Fe/H] $<$ 0.5 dex, and 4.0 dex $<$ log $g <$ 5.1 dex. Since the $T_{\rm eff}$ calibration is stable to moderate extrapolation beyond the published range, it can reliably identify stars that are hotter than our upper temperature limit. 946 of 1907, or 50%, of the stars screened meet the ideal temperature condition of $T_{\rm eff} \leq$ 6000K, and 1495 of our stars, or 78%, are cooler than 6400K. Figure 4 shows the $T_{\rm eff}$ distribution of the N2K targets.

The KSM planet search is primarily focused on stars with [Fe/H] ≥ 0.2 dex, which have a 10% or greater probability of having a gas giant planet (Fischer & Valenti 2005). 605, or 32% of the stars we screened, have [Fe/H] ≥ 0.2 dex. Of the 946 stars cooler than 6000K, 284 have [Fe/H] ≥ 0.2 dex. 431 stars with $T_{\rm eff} \leq$ 6400K have [Fe/H] ≥ 0.2 dex. Based on the planet-metallicity correlation reported by Fischer & Valenti (2005), the 284 ideal targets we have identified should harbor $\sim$ 17 giant planets detectable by Doppler searches, including $\sim$ 3 hot Jupiters. The 431 stars identified with $T_{\rm eff} \leq$ 6400K and [Fe/H] ≥ 0.2 should contain $\sim$ 30 detectable planets, including 4-5 hot Jupiters. 3 planets have already been discovered among the stars surveyed at KPNO (HIP 14810 is a double-planet system; see Wright et al. [2007]). Figure 5 shows the [Fe/H] distribution of the N2K targets. Table 3 contains the atmospheric parameters for the 1907 stars observed by the N2K KPNO program.

The planet detection rate per hour of Doppler surveys is limited by the exposure time required to reach high S/N. Although increasing the metallicity of targets by 0.1 dex increases the probability of planet detection around each star by 58% (Fischer & Valenti 2005), brightening targets in the V band by one magnitude means 2.5 times as many stars can be observed. Thus, a planet search focused on stars with $V = 8$ and [Fe/H] = 0.1 dex should detect more planets than a search allotted equal observing time, but targeting stars with [Fe/H] = 0.2 and $V = 9$. The targets surveyed at KPNO, members of the Hipparcos catalog (Perryman et al. 1997), were chosen from the brightest stars available that have not already been searched for planets. Instead of dipping into the voluminous Tycho II catalog (Høg et al. 1998) to select only stars with super-Solar metallicity estimates, we targeted Hipparcos stars with metallicity estimates from either the N2K broadband or the Nordström et al. (2004) $ubvy\beta$ calibrations of [Fe/H $\geq$ 0.0 dex. Stars with both $[\mathrm{Fe/H}]_{\mathrm{bb}} < 0.0$ dex and $[\mathrm{Fe/H}]_{ubvy\beta} < 0.0$ dex (where $[\mathrm{Fe/H}]_{\mathrm{bb}}$ is the metallicity measured from the N2K broadband calibration), or stars without $ubvy\beta$ photometry and with $[\mathrm{Fe/H}]_{\mathrm{bb}} < 0.0$ dex, were not considered for the KPNO survey. With this selection procedure, we could (1) enable the KSM planet-search team to identify bright stars with metallicity slightly below our ideal range, and (2) find stars with [Fe/H] $\geq$ 0.2 dex that were missed by the N2K broadband or $ubvy\beta$ calibrations. (For a description of the miss and false-positive rates of the photometric calibrations, see §5.)

Choosing planet-search targets with astrometric distance measurements vastly improves the ability to derive the stars' physical parameters, such as mass and, by extension, the semimajor axis of the planetary orbit. It is possible to solve for stellar mass and radius only from observed T_{eff} and log g by assuming a typical Pop I dwarf mass-to-light ratio, but mass and radius determinations based on direct distance measurements are far more accurate (see Valenti & Fischer [2005] for the procedure for calculating mass, radius and luminosity based on observed T_{eff}, [M/H], log g and distance). We targeted stars in the Hipparcos catalog for the KPNO program not only because of their relative brightness in comparison with the more numerous Tycho II stars, but because they have astrometric distance measurements. Most of the Hipparcos stars are too faint for the forthcoming 2.4m Automated Planet Finder telescope, which will seek low-mass companions around stars that have already been observed by Doppler surveys. By searching the Hipparcos catalog for giant planets, the KSM planet search fills an important niche: stars that have not yet been surveyed for planets, are too faint for small telescopes, and have astrometric distance measurements.

One final concern for planet searches is whether the target stars are members of multiple systems, because precise measurement of radial velocities is impeded when two spectra enter the slit. From a theoretical perspective, the orbit of a giant planet in a binary system can only be stable if it is circumbinary with a semimajor axis $a_{\rm pl}$ more than ~ 3 times the mean stellar separation a_*, or around one star only with $a_{\rm pl} \lesssim (1/3)a_*$. Multiple star systems may therefore have protoplanetary disks that are unstable for giant planet formation. An unusual case is the hot Jupiter orbiting the primary of the triple system HD 188753 (Konacki 2005). In Table 3, we note binary systems present in the SIMBAD astronomical database[3]. We also note stars that appeared to have a close companion on the 2.1m telescope slit camera, with a field of view $5'' \times 1\farcs3$, the slit width.

5. Performance of Broadband and $ubvy\beta$ Calibrations

In this section, we assess the N2K observing strategy. In brief, this consists of starting with Ammons et al. (2006) broadband (hereafter N2K broadband) or Nordström et al. (2004) $ubvy\beta$ (hereafter $ubvy\beta$) [Fe/H] estimates, refining these measurements with low-resolution spectroscopy at KPNO, placing the brightest and most metal-rich stars from the KPNO survey on the KSM planet-search target list, and finally, obtaining photometric observations to check hot-Jupiter candidates for transits. We report the numbers of misses and false positives produced by the photometric [Fe/H] and $T_{\rm eff}$ calibrations. (Ammons et al. (2006) did not build a photometric log g calibration.) Finally, we compare the precision of the N2K broadband, $ubvy\beta$, and Paper 1 calibrations, and discuss the benefits of obtaining the extra precision offered by low-resolution spectroscopy before proceeding to planet searches.

Although the broadband [Fe/H] calibration has uncertainty $\sigma \leq 0.17$ dex for stars brighter than $V = 9$, beyond this magnitude limit photometric errors increase the uncertainty of [Fe/H] estimates to $\sigma \geq 0.3$ dex. A target with $V = 9$ and $[{\rm Fe/H}]_{\rm bb} = 0.2$, or $P_{\rm planet} = 0.08$, has a 16% chance of having a true metallicity $[{\rm Fe/H}] \leq -0.1$ dex and $P_{\rm planet} = 0.02$, a 75% reduction in the probability of planet detection. This outcome is a "false positive," where a star appears to be above our ideal [Fe/H] for planet-search targets, but in fact is not. Since we are also looking for cool stars, another type of false positive is when a star is identified as having $T_{\rm eff} < 6400$K, but is in fact hotter. When targets are bright stars with astrometric distance measurements—ideal planet-search targets in every way except possibly metallicity, which is unknown—another problematic outcome is a "miss," where a star with that is truly metal-rich is identified as metal-poor. A miss also results when a cool star is mistakenly identified as having $T_{\rm eff} \geq 6400$K. Although the KSM planet search does observe stars with

[3]©ULP/CNRS - Centre de Données astronomiques de Strasbourg

[Fe/H] ≤ 0.2, its main focus is stars with super-Solar metallicity, [Fe/H] ≥ 0.2, so we will make this our metallicity cutoff. We set our temperature cutoff at $T_{\rm eff} = 6400$K, the point at which metal lines become too weak for planet searches.

"Hits," the most desirable outcomes of pre-planet-search screening, are stars with both $[{\rm Fe/H}]_{\rm bb}$ and $[{\rm Fe/H}]_{\rm KPNO} \geq 0.2$ (where $[{\rm Fe/H}]_{\rm KPNO}$ is metallicity measured from using the Paper 1 calibration on the KPNO spectra). A hit for the temperature calibration results when both $T_{\rm eff,bb}$ and $T_{\rm eff,KPNO}$ are lower than 6400K. The N2K broadband [Fe/H] calibration produced 485 hits, while the broadband $T_{\rm eff}$ calibration had 1388 hits. False positives are the least desirable outcome because they may lead to wasted time at large telescopes if stars are not screened with the Paper 1 calibrations. According to our KPNO $T_{\rm eff}$ measurements, the N2K broadband $T_{\rm eff}$ calibration only had 46 false positives, just over 3% of the stars it identified as cooler than our 6400K temperature limit. However, the broadband [Fe/H] calibration produced 337 false positives. If stars were selected for the KSM planet search based on broadband metallicity measurements alone, an unacceptable 38% of the stars on the target list would be false positives, as opposed to only 9% for the stars selected from KPNO observations plus broadband screening. (The Paper 1 calibrations would have much higher false positive and miss rates if tested on stars that had not been subject to photometric screening, since they are only valid for FGK dwarfs of approximately solar abundance mixture.) Figure 6 compares the performance of the broadband and Lick index calibrations for our set of VF05 stars observed at KPNO. Although both $T_{\rm eff}$ calibrations perform about equally well, the [Fe/H] measurements from KPNO spectra are noticeably more precise than those from the broadband [Fe/H] calibration.

Of course, not all false positives truly lead to wasted time on large telescopes: a star with [Fe/H] = 0.18 dex measured by the Paper 1 calibration, but 0.22 dex as measured by the N2K broadband calibration, is still a desirable planet-search target. We most want to flag false positives with dramatic metallicity overestimates, ~ 0.2 dex or more. Also, occasionally the broadband [Fe/H] measurement will be closer to the true value than the KPNO measurement: for the example quoted above, the 0.04 dex metallicity difference between the two estimates is within the error of the Paper 1 calibration. To get an idea of how often the broadband [Fe/H] calibration produces true misidentifications, we count the number of stars with $[{\rm Fe/H}]_{\rm bb} \geq 0.2 + \sigma_{\rm bb}$ but $[{\rm Fe/H}]_{\rm KPNO} < 0.2 - \sigma_{\rm KPNO}$. These are the false positives for which the error bars of the two calibrations do not overlap. There are 34 of these true false positives among the stars surveyed at KPNO; the KSM planet-search target list is therefore much cleaner as a result of having been vetted by the KPNO observations. Figure 7 shows a comparison of N2K broadband and KPNO [Fe/H] and $T_{\rm eff}$ measurements for all the stars screened at KPNO. Here again, we see that the temperature measurements from both calibrations match well, and the real gain provided by the KPNO observations is in precision of [Fe/H] measurements.

To measure [Fe/H] from $ubvy\beta$ photometry, Nordström et al. (2004) used the $ubvy\beta$-metallicity calibration of Schuster & Nissen (1989) (hereafter SN89), which has precision $\sigma = 0.13$ dex. For very red G and K dwarfs, however, the SN89 calibration produces large systematic errors in metallicity (Twarog, Anthony-Twarog & Tanner 2002); Nordström et al. (2004) thus derive a new $ubvy\beta$-metallicity calibration for cool G and K dwarfs. The $ubvy\beta$ [Fe/H] values were checked against the spectroscopic metallicities of Taylor (2003), Edvardsson et al. (1993) and Chen et al. (2000) and found to be in good agreement with each the values in each catalog.

We have two reasons for following up the fainter $ubvy\beta$ [Fe/H] estimates with low-resolution spectroscopy, and not adding the most metal-rich stars directly to the KSM planet search: (1) for stars with both N2K broadband and $ubvy\beta$ [Fe/H] estimates, there was often a discrepancy between the two calibrations of 0.2 dex or more, and (2) very few metal-rich stars were used to build the SN89 calibration. Martell & Laughlin (2002) noted [Fe/H] underestimates as a problem for metal-rich stars in SN89: a residual histogram for stars with $\mathrm{[Fe/H]_{spec}} \geq 0.0$ is centered at -0.08 dex. This systematic underestimate would lead to many misses. Of the 1907 stars surveyed at KPNO, 1052 have $ubvy\beta$ metallicity estimates and 184 stars have both $ubvy\beta$ and N2K broadband metallicity estimates. We count 227 misses and 61 false positives among the $ubvy\beta$ stars we surveyed, for a miss rate of 22%. 22 of the misses and 24 of the false positives were cases where the error bars of the $ubvy\beta$ and Paper 1 calibrations did not overlap. Figure 8 shows a comparison of the $ubvy\beta$ and KPNO [Fe/H] measurements.

Although the Paper 1 [Fe/H] calibration has quite high precision—enough to justify creating an observing program to screen planet-search targets—it has a limited range of use, only $-0.95 \leq \mathrm{[Fe/H]} \leq 0.5$ dex. Some type of photometric metallicity calibration is therefore absolutely necessary to weed out Population II stars and ensure that targets for low-resolution spectroscopy fall in the appropriate metallicity range. The Ammons et al. (2006) and Nordström et al. (2004) calibrations both perform this task admirably. As a result of the KPNO survey, we know that the N2K broadband T_{eff} calibration gives precise measurements even for stars dimmer than the published magnitude limit of $V = 9$, where photometric error is comparable to the internal calibration error. For future low-resolution spectroscopic surveys of this type, we can rely on the N2K broadband calibration to reject hot stars without any further verification. The N2K strategy of beginning with photometric [Fe/H] measurements, refining them by measuring Lick indices and using the Paper 1 calibrations, and finally placing the cool, metal-rich stars in the KSM planet search has so far been profitable, leading to the discovery of 3 new planets. We expect the N2K target list to be yielding new planet discoveries for some time.

6. Conclusion

We have calculated high-precision atmospheric parameters for 1907 FGK dwarfs in the Solar neighborhood. The ideal planet-search targets we identified will feed the Keck, Subaru and Magellan planet searches for the next 2 years. The 284 best targets, those with [Fe/H] $\geq$ 0.2 dex (for a $\geq$ 10% probability of harboring a detectable planet) and $T_{\rm eff} \leq 6000$K, should yield $\sim$ 17 new planet discoveries. The entire catalog of 1907 stars should eventually lead to $>$ 60 planet discoveries, including 8-9 hot Jupiters. Two hot Jupiters have already been found among our 1907 survey targets. As 10 of 48 known short-period planets display detectable transits, we hope that 1 or 2 additional transits may be found among the stars surveyed for this work. The high-quality planet-search targets identified by our low-resolution spectroscopic survey will keep the planet detection rate of the Keck/Subaru/Magellan program high, even as it pushes out to larger distances and fainter stars.

The N2K pipeline is an efficient and successful way to identify stars likely to host detectable planets. With the information from a single low-resolution spectrum, the calibrations in Paper 1 can provide atmospheric parameter measurements for any Pop I dwarf with precision rivaling some high-resolution surveys. Indeed, only 9% of the stars identified as having $[{\rm Fe/H}]_{\rm KPNO} \geq 0.2$, and observed once at Keck at the time of this writing, were found to have $[{\rm Fe/H}]_{\rm Keck} < 0.2$. The Ammons et al. (2006) temperature calibration is highly precise—$\sigma \leq 85$K for stars $V < 10$—and can be used on any dwarf star with $BVJHK$ photometry, which includes more than 100,000 stars in the Tycho II catalog (Høg et al. 1998). The N2K broadband and Nordström et al. (2004) $ubvy\beta$ metallicity calibrations are provide excellent first estimates of [Fe/H] and enable us to reject low-metallicity targets from our second-tier screening with low-resolution spectroscopy.

The main source of uncertainty in the N2K broadband [Fe/H] calibration is simply photometric error. A photometric catalog in which every measurement has the same S/N might make screening planet-search targets with low-resolution spectroscopy unnecessary. Indeed, the $ubvy$-metallicity calibration of Martell & Laughlin (2002), with precision $\sigma =$ 0.10 dex, was successful at identifying the first generation of Keck planet-search targets. Once the Hipparcos catalog has been thoroughly searched for planets, empirical metallicity calibrations could be created using $ugriz$ photometry from the Sloan Digital Sky Survey (Adelman-McCarthy et al. 2006). With over 6670 deg^2 surveyed, metal-rich, nearby stars from the SDSS catalog could feed automated planet-searches for generations to come, and enable such ambitious programs as taking the planet census of the entire Solar neighborhood.

Facility: KPNO:2.1m

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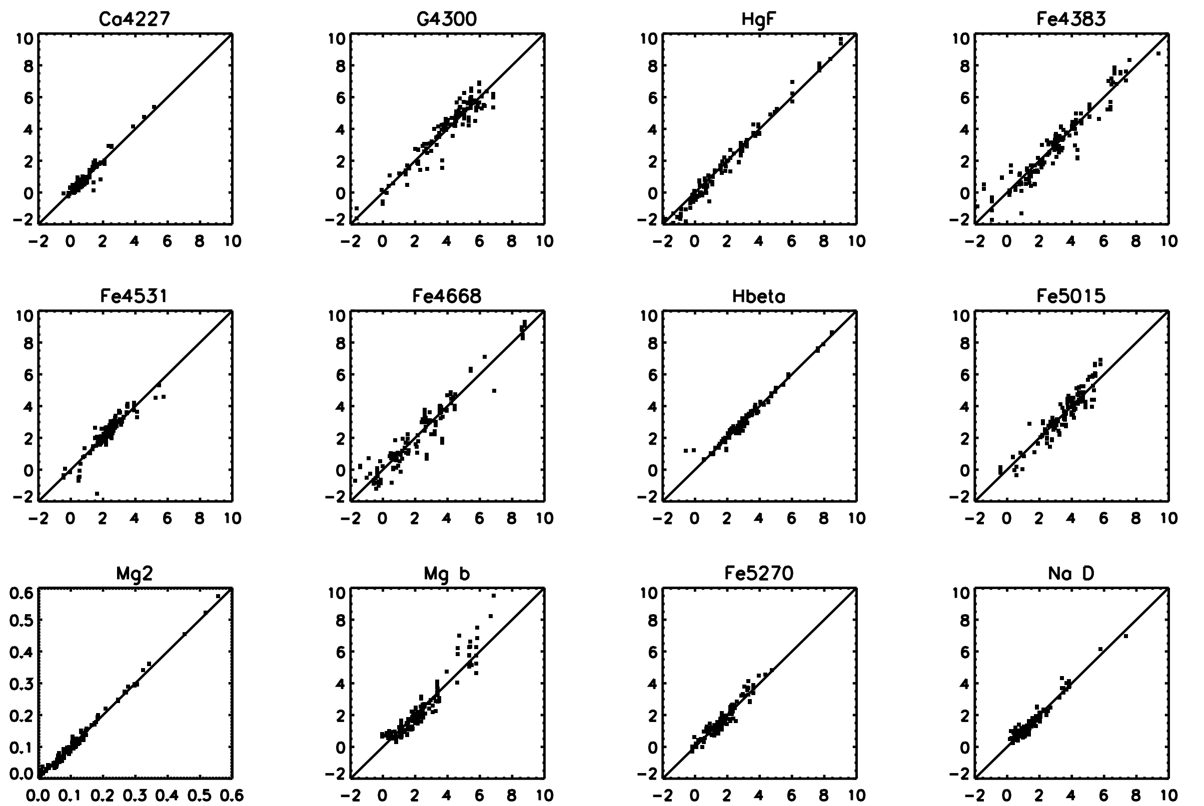

Fig. 1.— Comparison between observed equivalent widths (y-axis) and those published in Worthey et al. (1994) and Worthey & Ottaviani (1997) (x-axis) for the 12 indices used in the Paper 1 fits to stellar atmospheric parameters. Although separate transformations to the Lick system were calculated for each observing run, our program has nearly uniform precision in measuring Lick indices. All Lick standards observed in our program are shown together.

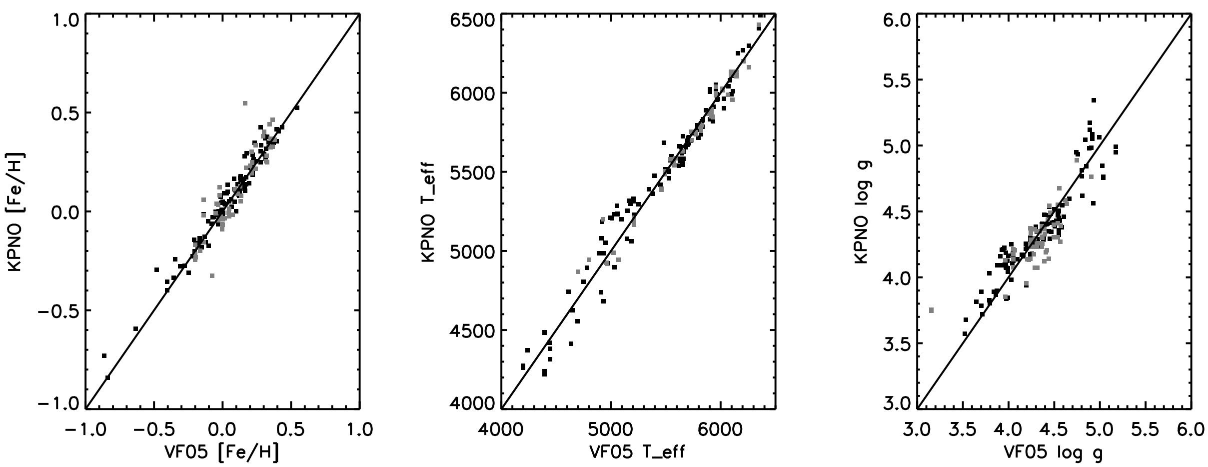

Fig. 2.— Test of Paper 1 calibrations. Stars that were used to build the calibrations are shown in black, and stars that were reserved for testing the calibrations are plotted in gray. The solid line shows a perfect 1:1 correspondence between our calibrations and VF05 measurements.

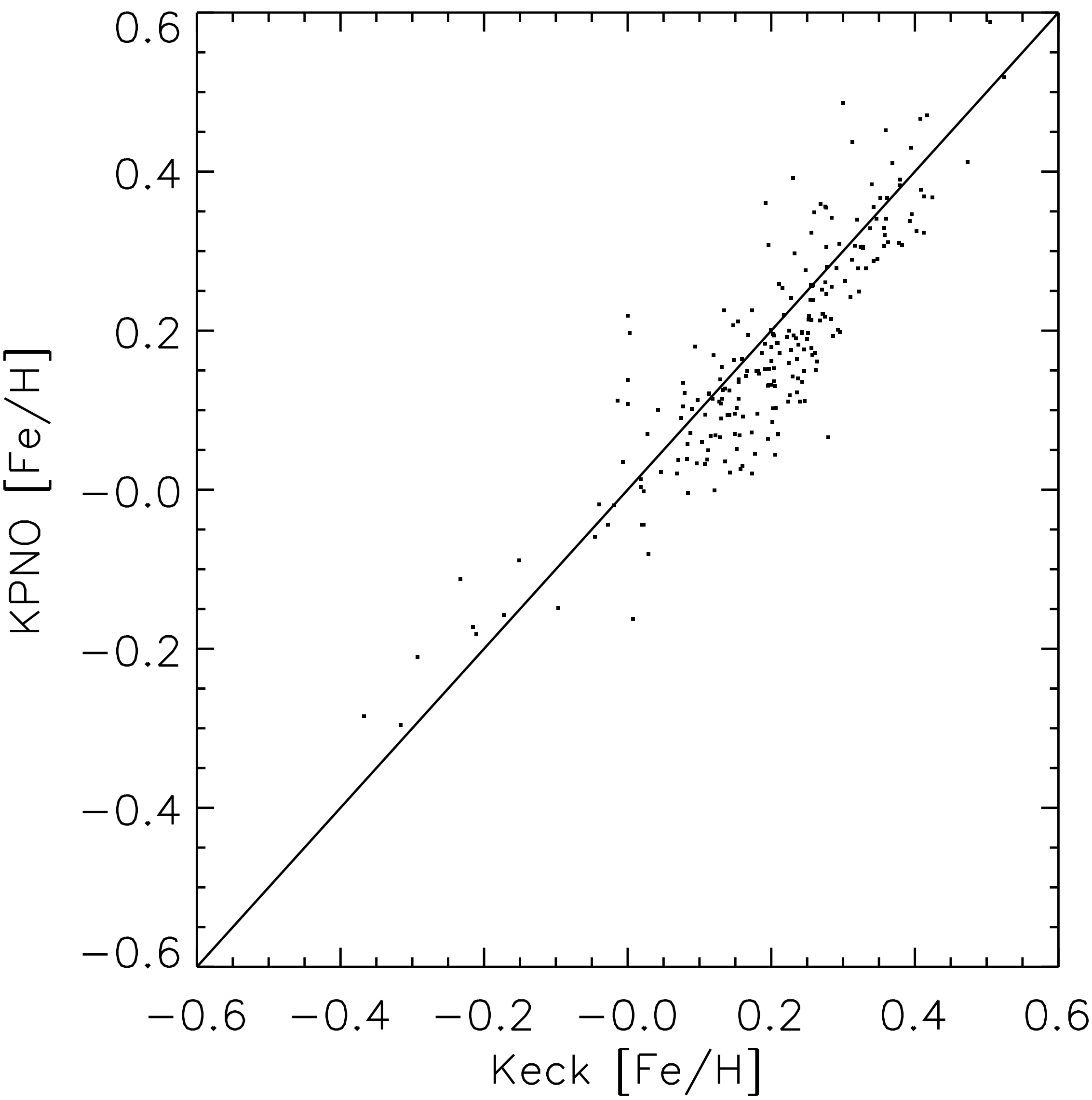

Fig. 3.— Verification of Paper 1 [Fe/H] calibration. For stars already observed as part of the Keck/Subaru/Magellan planet search at the time of this writing, [Fe/H] from the Lick Indices calibration is plotted as a function of Keck [Fe/H]. The measurements match well, with the standard deviation of (Lick index [Fe/H]) - (Keck [Fe/H]) at 0.07 dex.

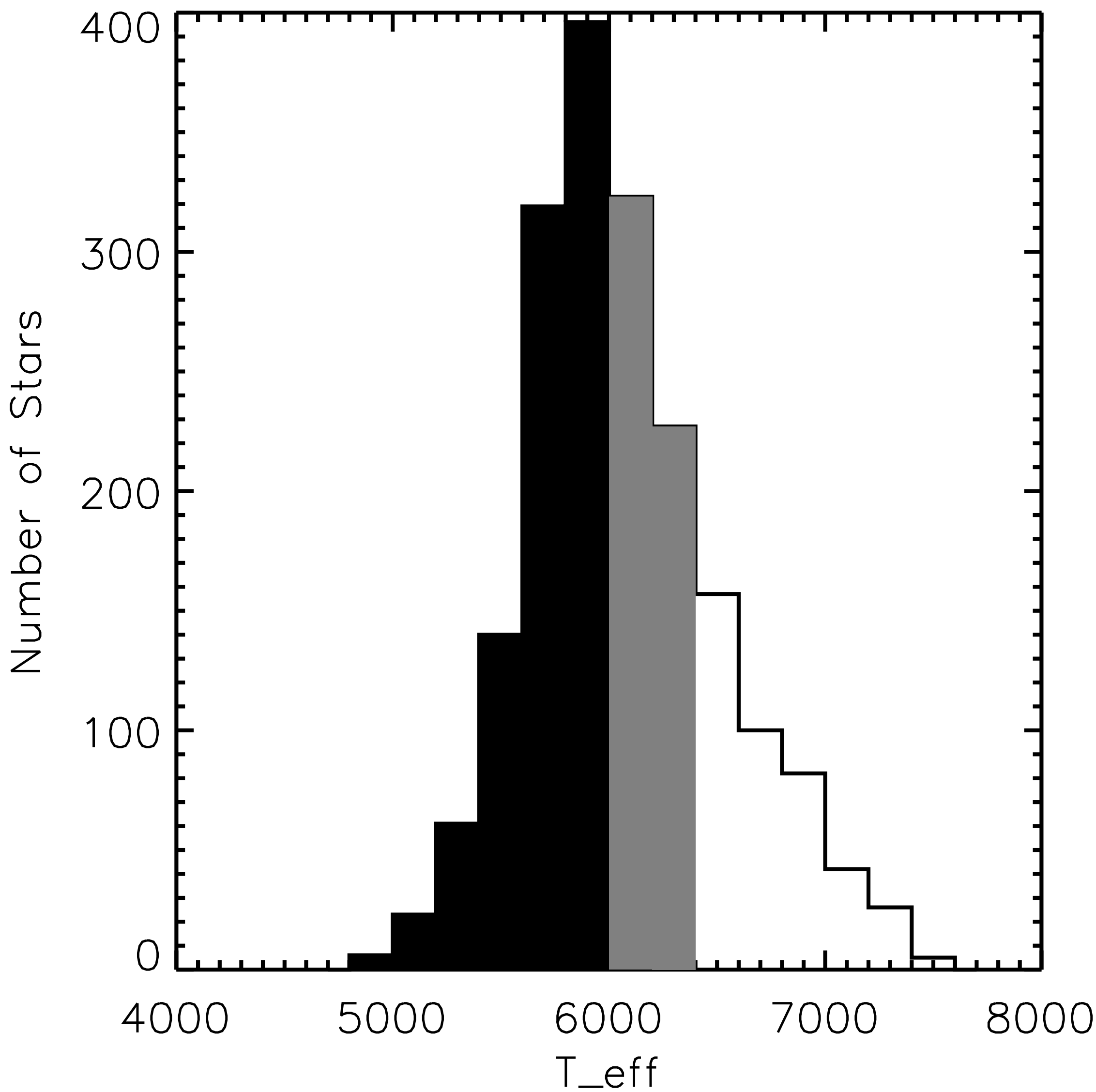

Fig. 4.— Histogram of effective temperature of the potential planet-search targets screened at KPNO. Planet searches are most effective for targets with $T_{\rm eff} \leq 6000$K (shaded black). 50% of our targets fall into this category. 78% of our targets are cooler than $T_{\rm eff} \leq 6400$K (shaded gray), where planet searches still get good results.

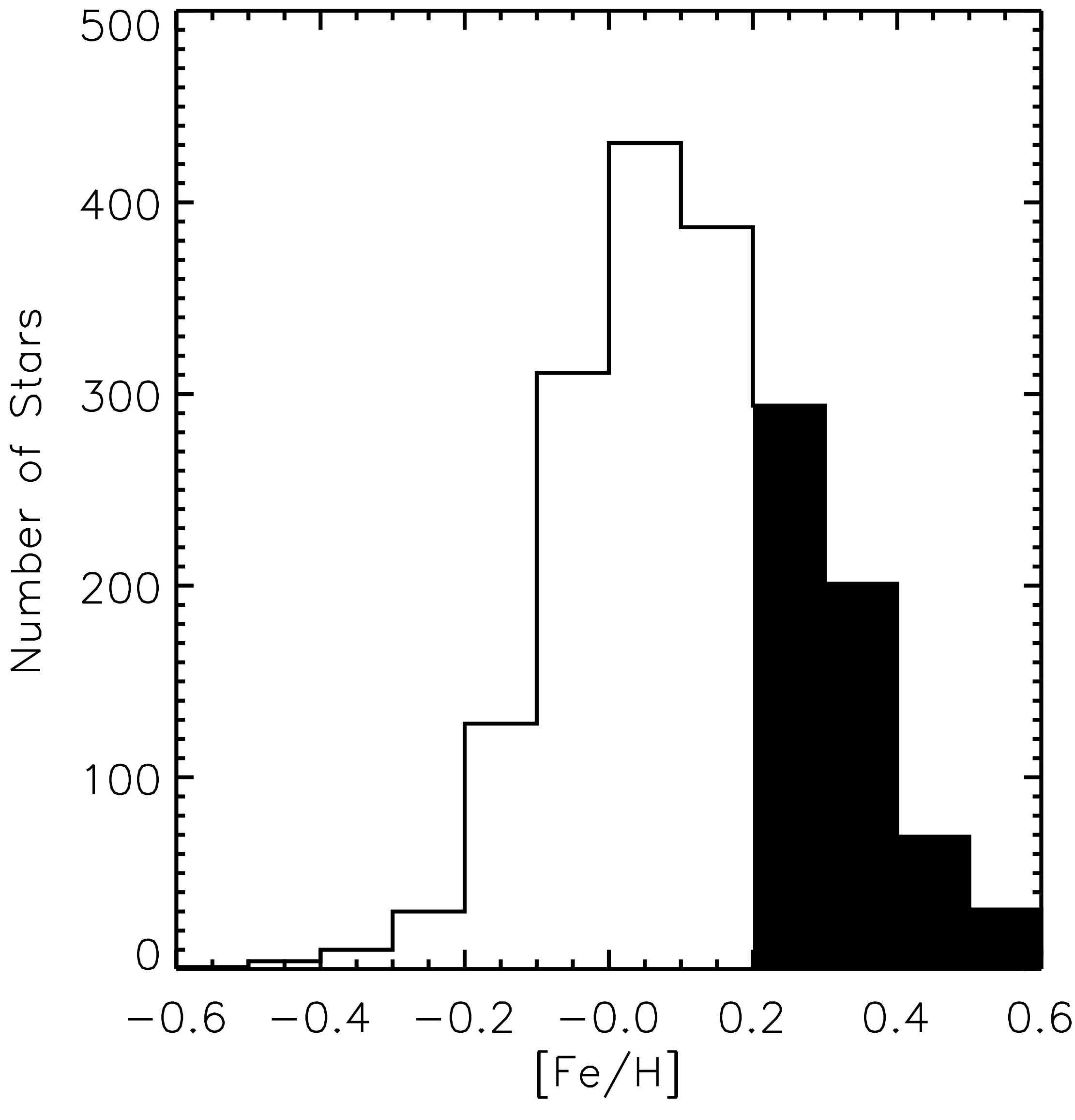

Fig. 5.— Histogram of metallicity of the potential planet-search targets screened at KPNO. 32% of the stars we surveyed have [Fe/H] ≥ 0.2, corresponding to a 10% or greater chance of harboring a detectable planet.

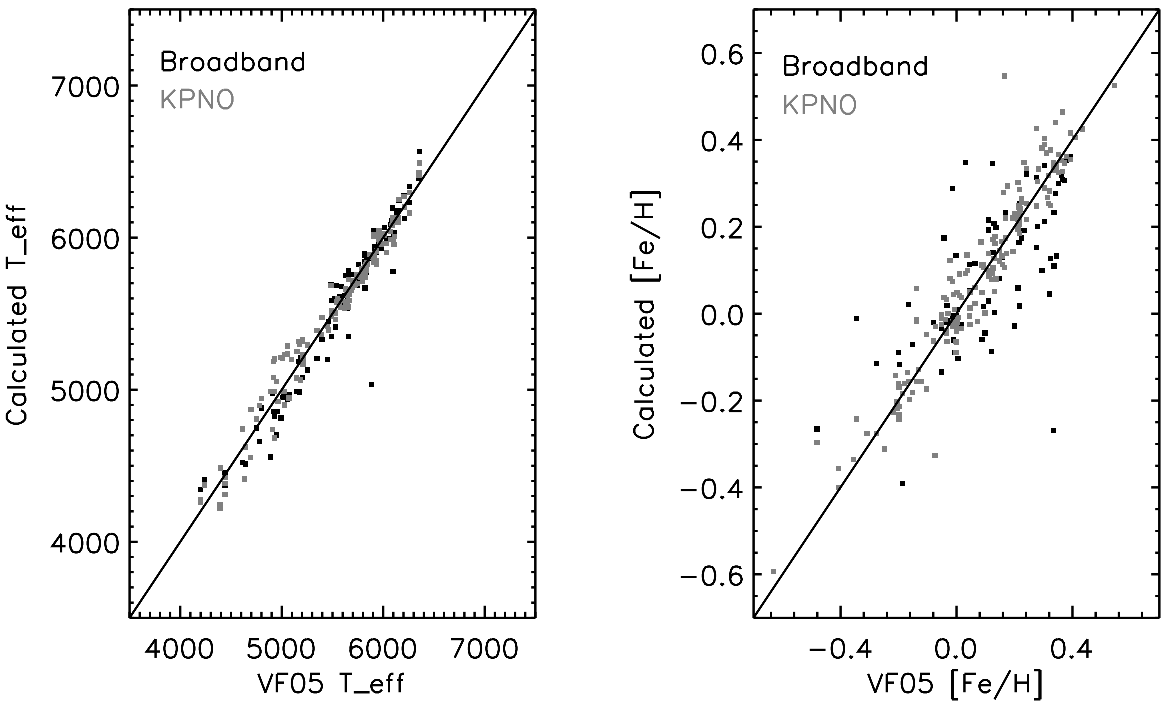

Fig. 6.— Performance of N2K broadband and Paper 1 calibrations for stars in common with VF05. Left: $T_{\rm eff}$; Right: [Fe/H]. Black symbols correspond to output of broadband calibration, and gray symbols indicate results of Lick indices calibration. The solid line in each plot shows a 1:1 correlation.

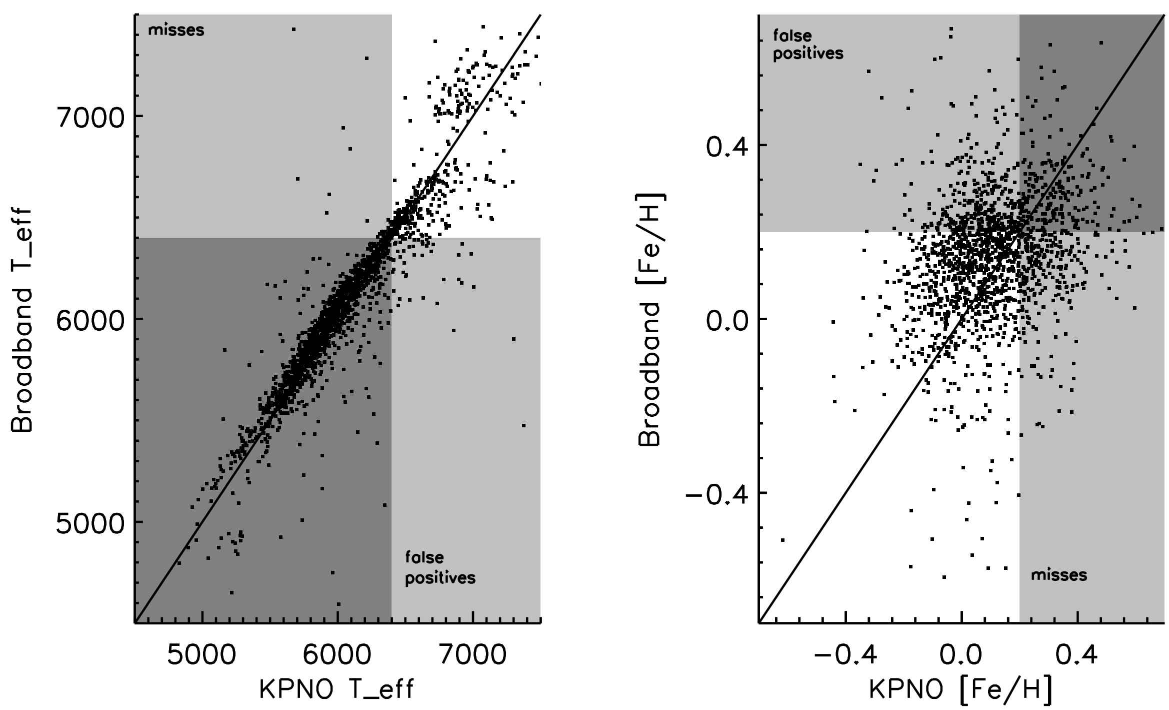

Fig. 7.— $T_{\rm eff}$ and [Fe/H] from broadband calibration as a function of values measured from the Paper 1 calibrations. Although the $T_{\rm eff}$ measurements from KPNO spectra give little gain in precision over the Ammons et al. (2006) values, [Fe/H] measurements from KPNO give a gain in precision of between 0.08 and 0.23 dex. The Paper 1 [Fe/H] calibration was able to reject 52 stars identified by the broadband calibration as being extremely metal-rich, but which in fact have 84% or higher probability of having [Fe/H] $<$ 0.2.

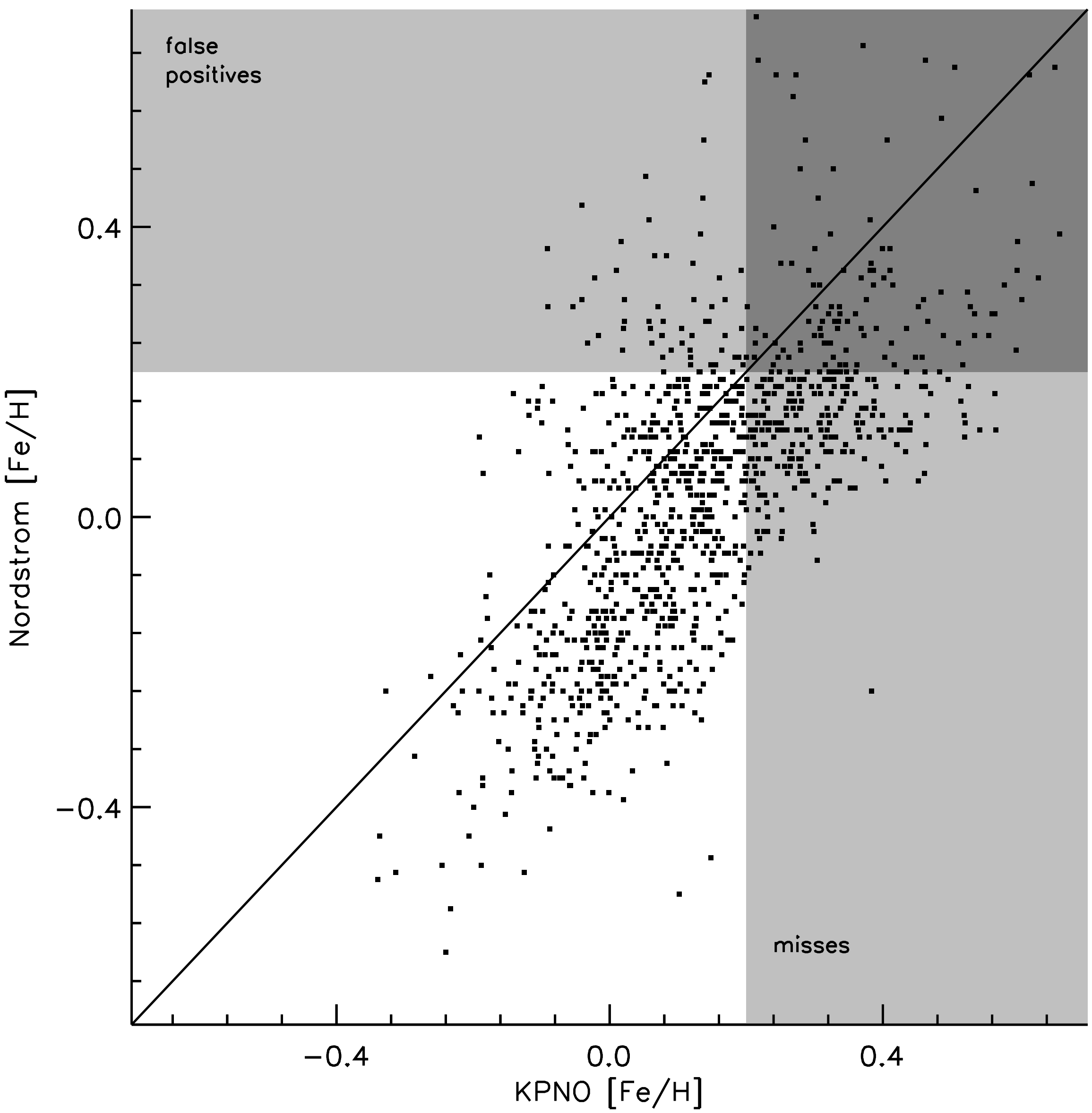

Fig. 8.— [Fe/H] from Nordström et al. (2004) *ubvyβ* photometry as function of values measured from Lick indices and Paper 1 calibration. The *ubvyβ* metallicities were mostly calculated with the Schuster & Nissen (1989) calibration, which was built for Pop II stars and is known to underestimate [Fe/H] for metal-rich stars. The scatter above [Fe/H] = 0.2 and the systematic [Fe/H] underestimates show that the Paper 1 calibrations provide a substantial improvement in precision and accuracy over the *ubvyβ* metallicities.

Table 1. Matching the Lick system: Linear transformations from observed to published Lick indices and index errors

Index	Slope	Intercept	Error	# Rejected[a]
Ca4227	1.101	-0.309	0.210	1
	0.844	0.108	0.274	1
	1.072	-0.103	0.194	0
G4300	1.229	-0.911	0.372	3
	1.410	-1.723	0.296	1
	1.782	-3.276	0.481	1
Hγ_F	1.068	-0.019	0.520	3
	1.199	-0.158	0.446	1
	0.980	0.128	0.230	1
Fe4383	0.975	-0.575	0.693	1
	0.928	0.300	0.615	0
	1.113	-0.254	0.543	2
Fe4531	0.988	-0.401	0.402	1
	0.948	-0.184	0.362	0
	1.097	-0.568	0.287	1
Fe4668	1.067	-0.234	0.607	2
	1.106	-0.533	0.554	1
	1.082	-0.249	0.529	2
Hβ	0.991	-0.133	0.161	2
	0.958	-0.045	0.359	1
	0.975	-0.128	0.198	2
Fe5015	1.055	-0.278	0.501	0
	0.962	-0.010	0.632	0
	1.087	-0.465	0.546	0
Mg_2	1.036	0.033	0.010	1
	0.995	0.047	0.009	0
	1.021	0.040	0.010	0
Mg b	1.376	0.518	0.355	2
	1.344	0.499	0.354	2
	1.231	0.606	0.457	0
Fe5270	1.186	-0.257	0.308	0
	1.044	-0.072	0.261	0
	1.107	-0.113	0.220	0
Na5895	1.149	-0.279	0.211	2
	0.933	0.354	0.211	1
	1.135	-0.143	0.282	0

[a]Number of points rejected from final compuatation of transformation

[b]Top row gives transformations for data taken in August 2004; middle row gives transformations for data taken in March 2005; bottom row gives transformations for data taken in April 2005